E. Friction Stir Joining and Processing of Advanced Materials, Including Metal Matrix Composites

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Objective

- Investigate and develop friction stir joining (FSJ) and friction stir processing (FSP) as viable industrial joining and processing techniques for advance materials including aluminum metal matrix composites (MMCs), titanium, and high-strength steel. This project includes three main task areas:

  — develop an appropriate tooling that will survive the abrasive and/or high-temperature environment found when friction stir joining or processing aluminum MMCs, steels, and titanium

  — investigate the FSP process to modify the surface of materials for advantageous near-surface mechanical and thermal properties

  — develop numerical models to help in the application of the process to new materials.

Approach

- Develop characterization and test methods to distinguish between different tool material/base material pairs.
- Develop a performance database of different bulk tool materials for FSJ/P of aluminum MMCs.
- Develop tool coatings as an alternative technique to prevent tool wear in a wide range of conditions.
- Experimentally determine the feasibility of making near-surface graded composites by FSP in aluminum, titanium, and steel to create functionally graded materials with enhanced surface properties.

- Develop numerical models that can describe the thermomechanical conditions and material flow during FSJ/P.

Accomplishments

- Developed test methods to distinguish between different tool material/base material pairs using instrumented plunge tests.
- Developed numerical models using modified computational fluid dynamics codes that describe material flow around tools as a form of Couette-Taylor Flow.
- Created near-surface regions in aluminum and steel that are enriched in ceramic particulate by physically stirring powders into the surface, utilizing a spinning friction stir tool.

Future Directions

- Further develop tool materials for steel and titanium FSJ/P.
- Develop process parameters and conditions necessary for surface modifications of steel and titanium.
- Develop friction stir surface processing for thermal barrier applications.
- Develop the process of reaction surface processing to create, by solid-state chemical reactions, new phases at the surface.

Introduction

Friction Stir Joining

Developing and manufacturing energy-efficient vehicles requires a multidisciplinary approach. One of the key strategies for making vehicles energy-efficient is to manufacture them from lighter materials. Structural and functional requirements, however, lead to a situation where no single lightweight material is appropriate for all applications. A modern, weight-optimized vehicle structure is a hybrid of many materials. A critical problem that has emerged in the development of these hybrid structures is that for many material combinations, traditional joining technologies (like fusion welding or mechanical fastening) are not appropriate. For some highly specialized materials, like aluminum MMCs, titanium, and high-strength steels, a better joining technology can have significant impact on whether these materials have a role in future vehicle structures.

In the past ten years a new joining technology, FSJ, has emerged that has the potential to join many lightweight materials. This process, invented by TWI, Ltd., is a solid-state process that employs severe plastic deformation to create joints between a wide variety of different materials. A typical FSJ butt joint is depicted in Figure 1. The weld is created by clamping the materials to be joined and plunging a spinning tool into the surface. The spinning tool is then translated down the joint line, leaving behind a weld zone characterized by a fine-grained, dynamically recrystallized microstructure. Typically, the tool is spun at 400 to 2000 rpm and translated down the joint line at a rate of 4 to 300 in./min depending on tool design, base material, and thickness. As the tool rotates and translates, complex flow patterns develop in the base material that create an intimate mixing of materials from both sides of the weld. Heat input during plastic deformation generally creates a temperature in the weld between 0.6 and 0.8° of the absolute

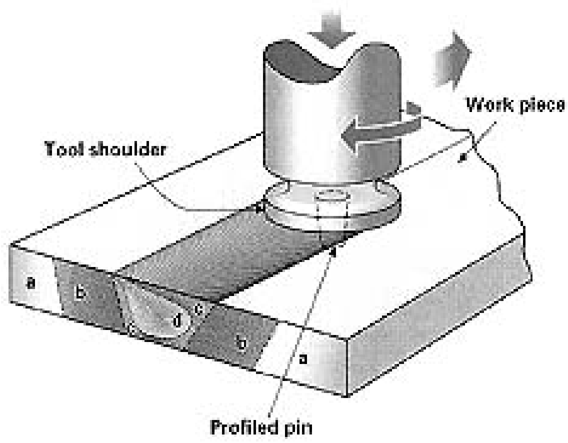

Figure 1. Friction stir joining and processing is accomplished by plunging a spinning tool into a material and translating the tool across the surface to form either a joint or a surface-processed region.

melting temperature, so no liquid phase is generated.

FSJ is capable of producing aluminum and magnesium alloy welds as good or better than fusion welds in terms of joint efficiency, mechanical properties, and environmental robustness. A significant advantage of the process for application to hybrid structures is that (because no melting occurs during the process) a large variety of dissimilar material joints are possible, including dissimilar aluminum and magnesium joints that are not possible with conventional fusion welding.

In the past five years, FSJ has been shown to be a commercially important, energy-efficient, and environmentally friendly process for joining aluminum. However, many opportunities exist for other higher-strength, lightweight materials to be considered if good joining technologies existed for these materials as well. The objective of this project is to investigate how FSJ can be applied to advanced materials, including Al-MMCs, titanium, and steels. Moving the FSJ process from “soft” materials like aluminum and magnesium into advanced, higher-strength alloys has proven to be challenging because of the mechanical and thermal demands on the tool materials. In steels, for instance, the tools must survive forge loads in excess of 10,000 lb and tool temperatures of 1100°C. A primary challenge is to develop pin tool designs and materials that can survive the high temperature and/or abrasive wear conditions under which the tool must operate.

Friction Stir Processing

Recently, a new research direction has emerged as an outgrowth of FSJ that recognizes that the same solid-state deformation process can be used to modify the surface of a monolithic material for enhanced properties. This new research direction is called friction stir processing (FSP).

Several applications of FSP have been investigated during the course of this project, including surface modification to improve wear resistance, create bulk superplastic properties, and improve the near-surface defect and porosity distribution in Al-MMC castings. Work during FY 2003 concentrated on the first application—creating a wear-resistant surface using FSP.

This work was designed to test the feasibility of using FSP to stir in ceramic particulate from the surface into a base material to produce a near-surface MMC. Work during previous years demonstrated that it is possible to create a discontinuously reinforced zone of 20-micron SiC or Al_2O_3 particles in a 6061 aluminum base alloy (Figure 2). Microscopy has shown that the stirred region is developed as deep as the pin probe (2 to 3 mm in our tests); it is defect free and forms a graded metallurgical bond with the underlying surface. No interface is developed between the composite zone and the base material. This process has the potential to produce a customizable surface. The surface zone has the potential to be orders of magnitude thicker than with conventional coating technologies, which has the added benefit of producing a graded structure that does

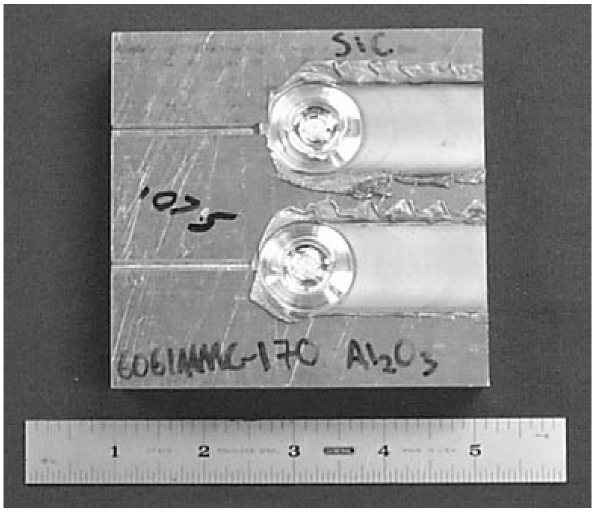

Figure 2. Friction stir processed 6061 plate with ceramic particulate incorporated into the surface by FSP

not have a sharp interface with the underlying substrate, thereby avoiding many of the problems seen in conventional coatings (CTE mismatch, etc.).

While lightweight, wear-resistant materials could benefit from this compositing technique, perhaps the greater application could be in ferrous or hard alloy systems. Hard particle reinforcement of the surface of steels, titanium, or brasses may have numerous industrial applications in reciprocating assemblies, engines, or other situations where both bulk strength and surface wear resistance is needed. Titanium or lightweight, high-strength steels with surface wear resistance may have numerous applications in both lightweight structures and lightweight vehicle power systems. Testing the feasibility of hard particle incorporation into titanium and steels is just beginning and will be a subject for next year's work.

Approach

The basic objective of this project is to investigate and develop FSJ and FSP as viable industrial techniques for advanced, lightweight materials. The approach is to (1) to develop new tool materials and designs that will allow us to make successful joints in Al-MMCs, titanium, and steel and (2) to explore the potential to modify the surface of conventional aluminum and magnesium alloys as well as advanced materials with the goal of improving wear, corrosion, or mechanical properties. This program is divided into three main tasks. The first task focuses on experimental testing of pin tool materials to identify critical factors for tool materials and design. The second task explores surface modification of metals by stirring ceramic powders into the surface to create functionally graded materials for wear and thermal management applications. The final task area supplements the first two and uses numerical modeling to gain understanding of material flow and microstructural development during FSJ/P to aid the design of appropriate FSJ tools.

Tool Materials Testing

Work during FY 2003 emphasized testing of appropriate tool materials for use in joining and processing aluminum-based MMCs. FSJ pin tool materials for joining and processing standard aluminum and magnesium alloys are hot-working tool steels (or Ni-alloy MP159 for harder 7xxx alloys). These tool materials show virtually no wear during FSJ/P of standard alloys. Al-MMCs, however, will cause significant tool wear after only a few inches of weld.

In an effort to characterize this wear and standardize it on a test method that could be used to compare many tool material–base material combinations, an instrumented plunge test system was implemented (Figure 3). These tests were designed to provide insight into the interaction between different tool materials and different types of Al-MMC base materials. Tool materials were plunged at a fixed load into the surface of 0.75-in.-thick MMC plates.

During the test, plunge rate, torque, and temperature were measured. Different tool materials showed significantly different

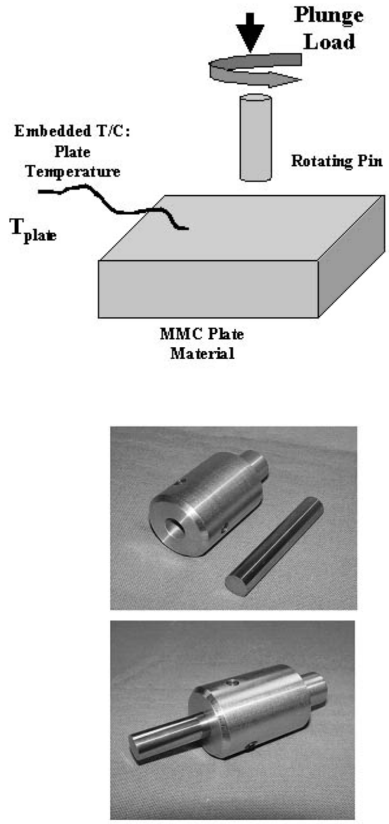

Figure 3. Schematic of instrumented plunge testing (top). Plunge pin in H13 tool holder (bottom). Test pins are fabricated from different materials and plunged into several different base materials to develop a test matrix.

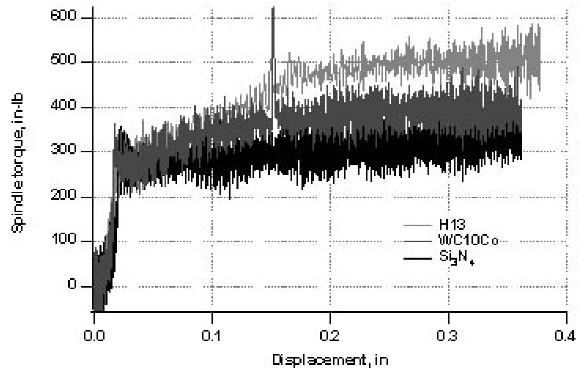

Figure 4. Graph of spindle torque vs. plunge displacement at a constant load. H13, tungsten carbide, and silicon nitride show different behavior in plunge testing.

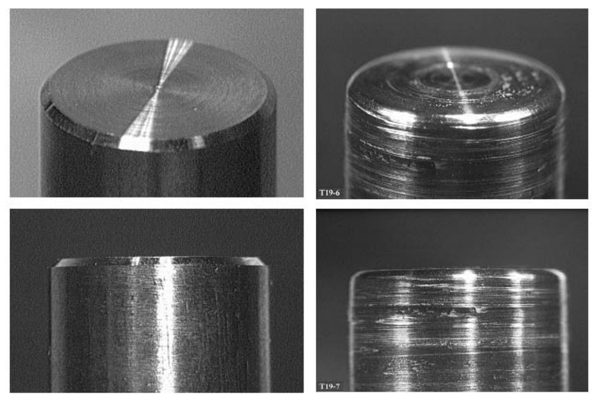

Figure 5. Wear performance of H13 in an instrumented plunge testing. The image on the right shows wear after 60 s of plunge testing.

plunge rates and spindle torques, as was expected from the heat flow characteristics of the tools. Three tool materials serve to bracket most of the plunge conditions encountered during testing—H13 tool steel, tungsten carbide, and silicon nitride (Figure 4). All other tool materials fall within a performance envelope defined by these three. For different combinations of tool and base materials, each of these had different plunge rates, heat generation, and base-metal deformation characteristics. Wear characteristics were also different, with H13 performing very poorly as expected (Figure 5), while the cemented carbides performed well. One of the best performers from a low tool wear perspective was a powder metallurgy ferrous MMC product composed of 35% rounded TiC particles in a matrix of impact- resistant tool steel.

Tool Coatings Development

Of all the tool materials tested during FY 2003, the best successes in terms of low tool wear were tungsten carbide with 10% cobalt and a TiC-reinforced, impact-resistant tool steel called Ferrotic. But even with these excellent materials, some wear still exists that can negatively impact tool survival in a volume joining application and negatively impact the joint integrity because of joint impurities. Therefore, the project has pursued the idea of tool coatings to prevent wear. Results from this year's work indicated that it is possible to protect the tool with an adhered layer of base metal promoted by tool coatings. Many candidate coatings were tested, but chrome carbide was the most successful in sticking aluminum base material to the face of a rod of H13 tool steel plunged into an MMC base plate (Figure 6). Surface wear on the tool was reduced under the adhered material.

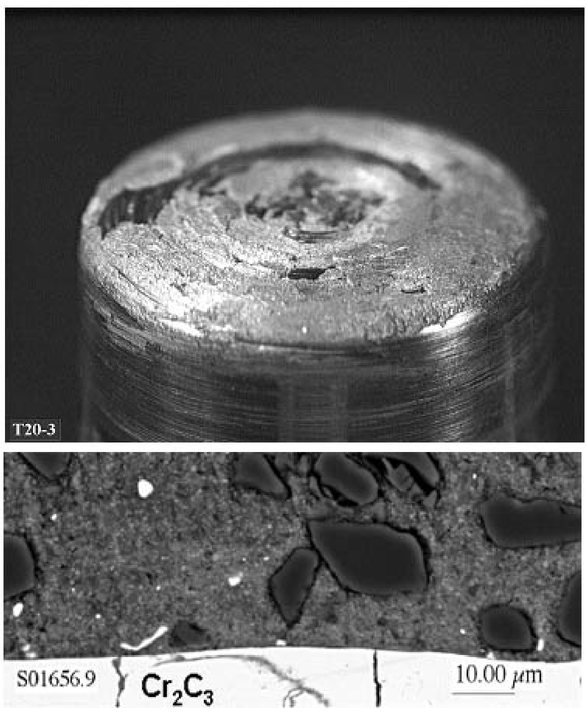

Figure 6. Chrome carbide coatings were successful in developing adhered metal zones on plunge pin tools (upper figure). Intimate, void-free contact exists between the Cr_2C_3 layer and the matrix aluminum (lower figure).

The study of coatings will continue in FY 2004 with the important goal of moving the idea into high-temperature materials. Coatings will be applied by electrospark deposition at Pacific Northwest National Laboratory (PNNL) and by laser deposition at the South Dakota School of Mines and Technology (SDSMT).

Another important discovery from the tool wear studies was that the bulk of the wear occurs during the initial tool plunge into the MMC base material. This is due in part to the higher flow stress of the initially cold material. To mitigate this, the project is now investigating the use of an induction preheater in front of the friction stir tool to preheat the base material. Work at SDSMT has also shown that using a preheater can increase welding speeds as well, which is an important consideration for the economics of volume applications.

Friction Stir Surface Processing

In FY 2003, the project was successful in creating functionally graded, near-surface MMC regions by friction stir surface processing. Two regions of particle enrichment were noticed—a near-surface region within 200 microns of the surface and a deeper region around the weld nugget. The surface region can contain as much as 50 area % ceramic particulate. The deeper region has a lower particulate area fraction, but in cross-section, it can show good distribution (Figures 7 and 8). These regions were created using a friction stir tool to physically stir surface-placed SiC powders into bulk 6061 T651 plate. Several tool

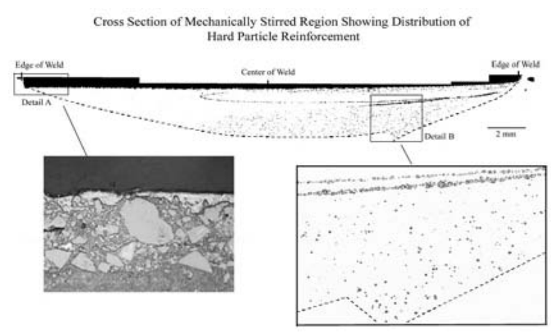

Figure 7. Silicon carbide distribution in 6061 T651 plate using a three-pin tool (PNNL internally funded work in FY 1999). Note the wide region of well-distributed particulate to a depth of 3 mm below the surface.

Figure 8. Silicon carbide distribution in 6061 T651 plate using a step spiral tool. High particle concentration occurs near the top surface, on the advancing side edge, and on the more homogeneous distribution in the nugget region.

designs were explored (Figure 9) in addition to many ceramic powder particle distributions and surface placement methods.

The work is ongoing to establish appropriate conditions for good particle distribution. One persistent feature noted from experimental work is that the particles tend to be distributed in regular bands. Figure 10 shows the distribution of particulate 0.025 in. below the surface (plan view). Figure 11 shows a cross-section micrograph of one of these bands showing the increase in microhardness within the band caused by fine ceramic particulate reinforcement. Microhardness values in the particle-enriched areas are over twice that in the bulk material and are periodic because of the banded distribution (Figure 12).

Experimental work at SDSMT has also revealed the possibility of creating in situ surface composites. When the precursor powders include both SiC and aluminum powder, the surface-processed regions contain an abundance of a fine-grained Al-Fe-Si intermetallic. This reaction is occurring well below the temperatures normally needed, which suggests the possibility that the severe plastic deformation that occurs in FSP may be providing energy for some solid-state reactions that were not previously anticipated. Thermodynamic calculations on numerous potential solid-state reactions

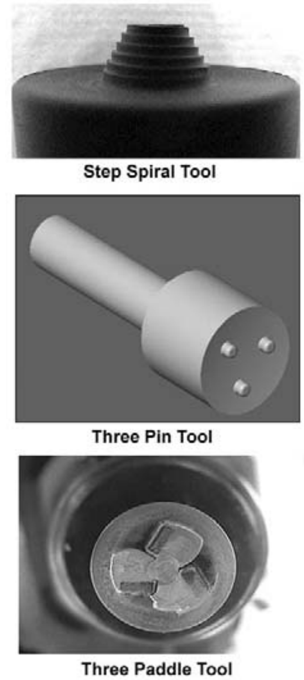

Figure 9. Different tool designs produce different particle distributions and flow characteristics

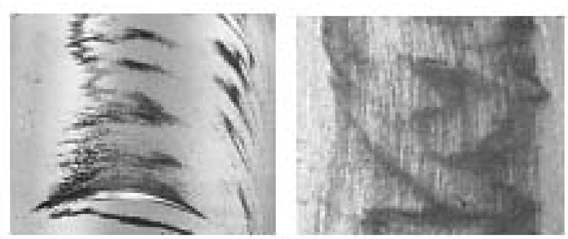

Figure 10. Plan view section cut 0.025 in. below the surface of the weld, showing banded distribution of SiC particulate when using a step spiral tool.

indicate that energies available during FSJ/P may be high enough to initiate the formation of some compounds, like TiB_2, from elemental constituents, especially considering all the new surface being generated by the severe plastic deformation under the pin tool. Project activities next year will include pursuing this work in aluminum, as well as in steels and titanium where in situ composites may have even greater application than in the aluminum system.

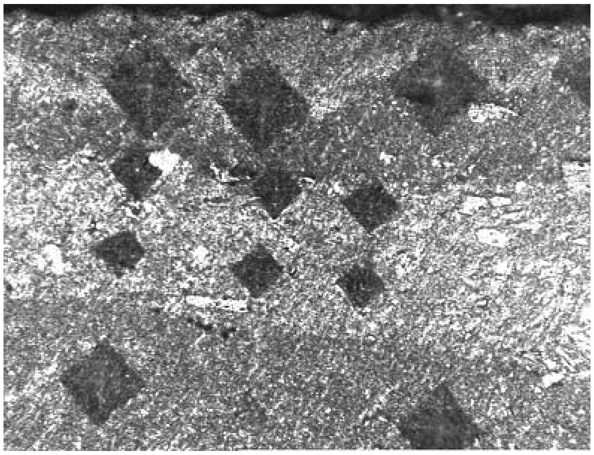

Figure 11. Microhardness across SiC particle-rich band.

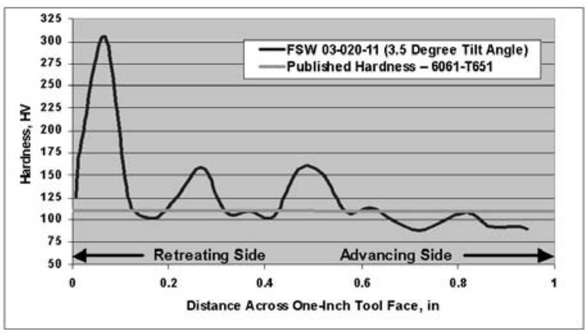

Figure 12. Microhardness values taken perpendicular to weld travel direction, showing periodic hardness distribution caused by the banded structure.

With these successes, researchers are now stirring powders into higher-temperature base materials. At present, we are stirring TiB_2 into 1018 steel and anticipate moving to titanium 6-4 by early 2004. FSP of ferrous or titanium materials is a technology in its infancy. Very little is known about processing conditions needed to incorporate powders or even about the feasibility of the process in some metallurgical systems. Also, use of this process to create ceramic particulate-reinforced surface zones in steel or titanium requires high-temperature FSP tools. Although some interim solutions exist for the high-temperature tool wear issue (this project uses high-density tungsten, 25% rhenium, and/or polycrystalline cubic boron nitride tools), tool survivability is an area that needs to make progress before the process can be fully implemented into the domestic industry.

Conclusions

FSJ/P technologies will enable the application of many lightweight materials in the next generation of transportation systems. Many advanced materials, such as Al-MMCs and certain high-strength steels, are in need of lightweight, cost-effective joining technologies before their widespread use is considered. Solid-state FSJ/P avoids many of the problems with fusion joining and represents a revolutionary change in joining technology. Problems still exist, however, mostly related to the survivability of tool materials during joining. A companion program at Oak Ridge National Laboratory is making significant advances in the development of bulk, high-temperature tungsten-based tool materials, and research at PNNL is focusing on coating strategies in an ongoing effort to address the tool-wear issues. The results of this work will allow designers to anticipate structures that are a hybrid of many different materials joined together into lightweight assemblies. These results will help achieve the goal of producing lighter and more fuel-efficient vehicles.